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Muon Charge Ratio of Ultrahigh Energy Cosmic Rays*

BO-QIANG MA

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
mabq@phy.pku.edu.cn

The muon charge ratio of ultrahigh energy cosmic rays may provide information to detect the composition of the primary cosmic rays. We propose to extract the charge information of high energy muons in very inclined extensive air showers by analyzing their relative lateral positions in the shower transverse plane.

The most high energy particles can be observed by human being are from cosmic rays. The study of them belongs to frontiers of human knowledge in combination of cosmology, astrophysics, and particle physics, and can provide better understanding of the universe from most small to most big, i.e., connecting quarks to the cosmos. The universe is not empty, but full of background relic particles from the big bang. It has long been anticipated that the highest energy cosmic rays would be protons from outside the galaxy, and there is an upper limit of the highest energy in the observed proton spectrum, commonly referred to as the GZK cutoff [1], as the protons traveling from intergalactic distances should experience energy losses owing to pion productions by the photons in the cosmic background radiation. Although there have been attentions for the cosmic ray events above the GZK cutoff, it is natural to expect that these ultrahigh energy cosmic rays come from sources within the GZK zone [2], i.e., not far from us in more than tens of Mpc. Recently there are also reports on the observation of the GZK cut-off by new experiments [3]. However, questions about the composition of such ultrahigh energy cosmic ray particles, e.g., whether they are protons, neutrons, or anti-nucleons [4], are still open to investigations.

Muons in the air showers are mainly from decays of pions and kaons produced in the interactions of the primary cosmic rays with the atmosphere. The very high energy secondary pion and kaon cosmic rays can be considered as from the current fragmentation of partons in deep inelastic scattering of the primary cosmic rays with the nucleon targets of the atmosphere in a first approximation [5]. We also consider only the favored fragmentation processes, i.e., the π^+, which is composed of valence u and $\bar{d}$ quarks, is from the fragmentation of u and $\bar{d}$ quarks in the nucleon beam,

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and the π^-, which is composed of valence $\bar{u}$ and d quarks, is from the fragmentation of $\bar{u}$ and d quarks [6]. Similarly, the K^+, which is composed of valence u and $\bar{s}$, is from the fragmentation of u and $\bar{s}$ quarks, and the K^-, which is composed of valence $\bar{u}$ and s, is from the fragmentation of $\bar{u}$ and s quarks. The μ^+ is from the decay of a π^+ or a K^+ and the μ^- is from the decay of a π^- or a K^-. We can roughly estimate the muon charge ratio by

$$\frac{\mu^+}{\mu^-} = \frac{\int_0^1 \mathrm{d}x \left\{ \left[u(x) + \bar{d}(x)\right] + \kappa \left[u(x) + \bar{s}(x)\right] \right\}}{\int_0^1 \mathrm{d}x \left\{ \left[d(x) + \bar{u}(x)\right] + \kappa \left[\bar{u}(x) + s(x)\right] \right\}}, \tag{1}$$

where $q(x)$ is the quark distribution with flavor q for the incident hadron beam and $\kappa \sim 0.1 \rightarrow 0.3$ is a factor reflecting the relative muon flux and fragmentation behavior of K/π. Secondary collisions do not influence the above estimation, since the current parton beams still keep their flavor content and act as the current partons after the strong interactions with the partons in the atmosphere targets. Adopting a simple model estimation of the parton flavor content in the nucleon without any parameter [7], we find that $\mu^+/\mu^- \sim 1.7$ for proton and $\mu^+/\mu^- \sim 0.7$ for neutron. This simple evaluation is in agreement with the empirical expectation of $\mu^+/\mu^- \approx 1.66$ for proton and $\mu^+/\mu^- \approx 0.695$ for neutron [8] as well as that in an extensive Monte Carlo calculation [9], thus it provides a clear picture to understand the dominant features for the muon charge ratio by the primary hadronic cosmic rays. For the μ^+/μ^- ratio for antiproton, it is equivalent to the μ^-/μ^+ ratio for proton by using Eq. (1), thus we find $\mu^+/\mu^- \sim 0.6$ for antiproton, which is close to that for neutron. The μ^+/μ^- ratio for antineutron is also equivalent to the μ^-/μ^+ ratio for neutron, and it is $\mu^+/\mu^- \sim 1.4$, which is close to that for proton. It is hard to distinguish between the primary neutrons and antiprotons (or protons and antineutrons) by the μ^+/μ^- ratio of the air shower, unless very high precision measurement is performed and also our knowledge of the muon charge ratio for each nucleon species is well established.

The study of cosmic rays with primary energies above 10^5 GeV are typically based on the measurements of extensive air showers (EAS) that they initiate in the atmosphere. The ground detector array records the secondary particles produced in shower cascades, including photons, electrons (positrons), muons, and some hadrons. Then their arrival times and density profiles are used to infer the primary energy and composition of the incident cosmic ray particle, usually through comparison with simulated results. Photons, electrons and positrons are the most numerous secondary particles in an EAS event. However, for very inclined showers, these electromagnetic components would travel a long slant distance and are almost completely absorbed before they reach the ground. On the other hand, muons are decay products of charged mesons in shower hadronic cascades. Most high energy muons survive their propagation through the slant atmospheric depth, during which they lose typically a few tens of GeV's energy. These high energy muons carry important information about the nature of the primary cosmic ray hadron, which will be extracted from their energy spectrum and lateral distribution.

As discussed by Hwang and I [4], the ratio of positive versus negative muons μ^+/μ^- is a significant quantity which can help to discern the primary composition, and at high energies this charge ratio also reflects important features of hadronic meson production in cosmic ray collisions. In order to obtain such muon charge information, we would need a way to distinguish between positive and negative high energy muons. Unfortunately, existing muon detectors available at shower arrays, usually scintillators and water Čerenkov detectors, are not commonly equipped with magnetized steel to differentiate the muon charges. Even if they were, the limited region of the magnetic field prevents definite determination of high energy muons' track curvature.

This invites us to think of the geomagnetic field as a huge natural detector for muon charge information. Apparently, after being produced high in the atmosphere, a positively charged muon would bend east on its way down while a negatively charged muon would bend west, introducing an asymmetry into the density profile of the shower front. If their separation is large enough as compared with other circularly symmetric "background" deviations, it will be possible to distinguish the positive muons from the negative ones.

To see such an effect, Xue and I [10] analyzed the possibility of obtaining the charge information of high energy muons in very inclined extensive air showers. We have demonstrated that positive and negative high energy muons in sufficiently inclined air showers can be distinguished from each other through their opposite geomagnetic deviations in the transverse plane. We developed a revised Heitler model to calculate this distinct double-lobed distribution, and studied the condition for the two lobes of either positive or negative muons to be separable with confidence. From our criterion of resolvability, we concluded that a zenith angle $75° \leq \theta \leq 85°$ will be most suitable for our approach.

There are already some results from full air shower simulations that take into account the geomagnetic effect on muon propagation [11,12,13,14,15,16,17,18]. They illustrated remarkable double-lobed muon lateral density profile in very inclined air showers, which is in agreement with our expectation qualitatively. However, no present study has fully considered the high energy part of muon content, which can be used to compare with our results. Thus we would like to propose future simulations of very inclined extensive air showers that focus on the behavior of high energy muons. They also have to keep track of the muon charges and the relation to their lateral positions. For more detailed analysis and discussion, please refer to Ref.[10].

In summary, we propose to extract the charge information of high energy muons in very inclined extensive air showers by analyzing their relative lateral positions in the shower transverse plane. This muon charge information is helpful to detect the composition of cosmic rays, e.g., the neutron or antiproton content of the ultrahigh energy cosmic rays.

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